PB86-164902

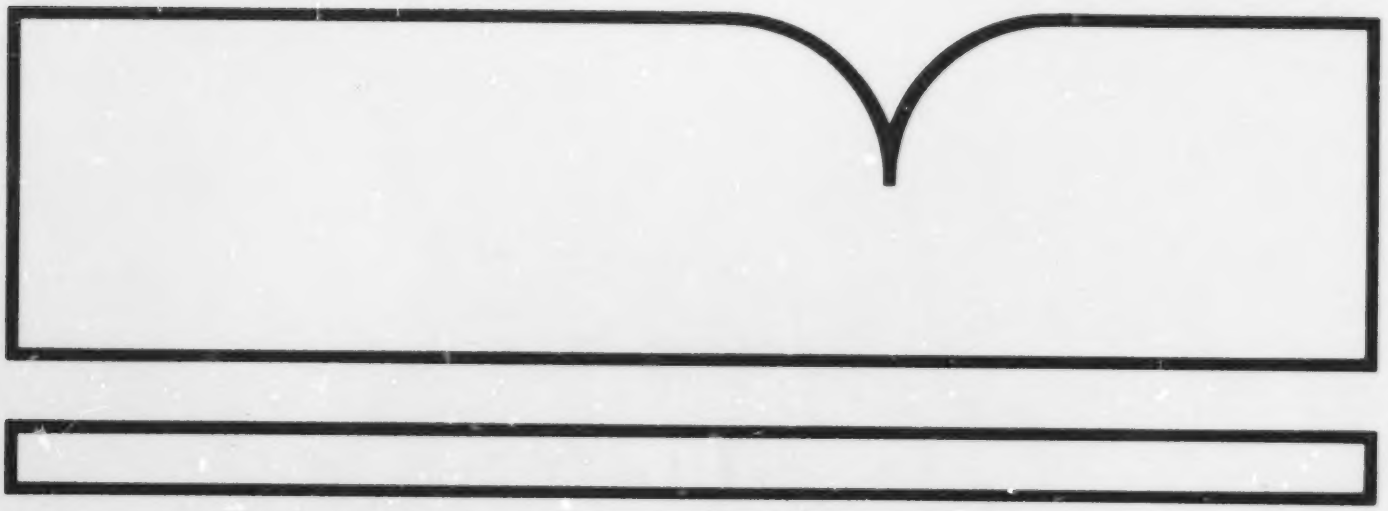
Determining Uncertainty in Physical Parameter Measurements by Monte Carlo Simulation

Research Triangle Inst.
Research Triangle Park, NC

Prepared for

Environmental Protection Agency, Washington, DC

Mar 86



U.S. Department of Commerce
National Technical Information Service
NTIS

PB86-164902

EPA/600/D-86/052
March 1986

DETERMINING UNCERTAINTY IN PHYSICAL PARAMETER MEASUREMENTS BY MONTE CARLO SIMULATION

by

David W. Coy,[1] Gregory A. Kew,[2]
Michael E. Mullins,[1] and Phillip V. Piserchia[1]

[1]Research Triangle Institute
Research Triangle Park, NC 27709

[2]Office of Health and Environmental Assessment
U.S. Environmental Protection Agency
Washington, DC 20460

EPA Contract 68-03-3149

EPA Project Officer
James Bridges

OFFICE OF HEALTH AND ENVIRONMENTAL ASSESSMENT
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, DC 20460

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA/600/D-86/052		PB86 164902/AS

4. TITLE AND SUBTITLE	5. REPORT DATE
Determining Uncertainty in Physical Parameter Measurements by Monte Carlo Simulation	March 1986
	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
David W. Coy, Gregory A. Kew*, Michael E. Mullins and Phillip V. Piserchia	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Research Triangle Institute P.O. Box 12194 Research Triangle Park, NC 27711 * Office of Health & Environmental Assessment (RD-689) U.S. EPA 401 M St. SW. Washington, DC 20460	11. CONTRACT/GRANT NO. 68-03-3149, Work Assignment 15-2

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Office of Health and Environmental Assessment (RD-689) U.S. EPA 401 M Street SW. Washington, DC 20460	14. SPONSORING AGENCY CODE EPA/600/21

15. SUPPLEMENTARY NOTES

16. ABSTRACT

A statistical approach, often called Monte Carlo Simulation, has been used to examine propagation of error with measurement of several parameters important in predicting environmental transport of chemicals. These parameters are vapor pressure, water solubility, octanol-water partition coefficient, and "volatilization from water" (based on the ratio of laboratory-measured volatilization rate constant to oxygen reaeration rate constant for a specific system). Column chromatographic and high pressure liquid chromatographic (HPLC) methods tend to underpredict aqueous solubility and vapor pressure and overpredict octanol-water partition coefficient. Measurement error proves not to be normally distributed, with differing bias for each parameter. For "volatilization from water", determination of the ratio of rate constants for compounds whose Henry's Law constant equals or exceeds 1,000 torr/mole/liter typically report 95% confidence limits equal to 5 to 10 percent of the ratio. Analysis of a regression approach often used to determine the ratio suggests underestimation of both the ratio and its variance. Monte Carlo simulation did not confirm underestimation of the ratio but suggests variances may be underestimated by a factor of 2.3. Using this statistical approach in other cases might allow an investigator to choose levels of a parameter (e.g. a drinking water standard) knowing the uncertainty associated with the choice, or the converse.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Uncertainty Uncertainty Analysis Monte Carlo Simulation Stochastic Methods		

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Unlimited	Unclassified	29
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Determining Uncertainty in Physical Parameter Measurements by Monte Carlo Simulation

David W. Coy, Gregory A. Kew*,
Michael E. Mullins and Phillip V. Piserchia

Research Triangle Institute
P.O. Box 12194
Research Triangle Park, NC 27709

*Office of Health and Environmental Assessment (RD-689)
U.S. Environmental Protection Agency
Washington, DC 20460

A statistical approach, often called Monte Carlo simulation, has been used to examine propagation of error and to better characterize the uncertainty associated with measurement of several parameters important in predicing environmental transport of chemicals. These parameters are vapor pressure, water solubility, octanol-water partition coefficient, and "volatilization from water" (based on the ratio of laboratory-measured volatilization rate constant to oxygen reaeration rate constant for a specific system). Column chromatographic and high pressure liquid chromatographic (HPLC) methods are replacing more traditional equilibrium methods (e.g. shake flask, isoteniscope) for measuring the first three parameters. The newer methods tend to underpredict aqueous solubility and vapor pressure and overpredict octanol-water partition coefficient, although deviations for both the equilibrium and dynamic systems are similar. Measurement error proves not to be normally distributed, with differing bias for each parameter. For "volatilization from water", determinations of the ratio of rate constants for compounds whose Henry's Law constant equals or exceeds 1,000 torr/mole/liter typically report 95% percent confidence limits equal to 5 to 10 percent of the ratio. Analysis of a regression approach often used to determine the ratio suggests underestimation of both the ratio and its variance. Monte Carlo simulation did not confirm underestimation of the ratio but suggests variances may be underestimated by a factor of 2.3. Using this statistical approach in other cases might allow an investigator to choose levels of a parameter (e.g. a drinking water standard) knowing the uncertainty associated with the choice, or the converse.

The purpose of this study is to illustrate a statistical approach for determining overall uncertainty in a parameter calculated from more than one input, when distribution of error for the inputs can be estimated. The approach incorporates this information into a concise statement of overall uncertainty. In particular, it permits determining the probability of exceeding a specific level. The results then are compared with error estimates for specific experimental procedures in the literature.

This approach seems applicable to broader investigations than are explored here, such as predicting environmental transport and fate of chemicals where properties of various compounds are used in models. Even more generally, it might be applied to exposure assessment where, usually, too few data are available to characterize distributions of exposure to particular chemicals.

General approaches for expressing uncertainty most evident in the literature may be viewed as various forms of "propagation of error." Variants range from "sensitivity analysis" where the effects of individual input variables are examined by holding all other variables at midrange while the one under study is varied from minimum to maximum, to the use of fixed formulae derived for various mathematical relationships in specifying absolute maxima and minima for outputs. None of these methods can supply a probability of occurrence for a given value within the range of possible error.

What appears to be yet another variant, a statistical approach often called Monte Carlo simulation, recently has been demonstrated to apply by Walentowicz and Falco if the distribution of values for each input variable is known or can be approximated (1). Thereafter, this information can be manipulated to yield a distribution of outputs expressing probability of occurrence for any given value. Also, a recent study by Whitmore (2) develops the concepts of Walentowicz and Falco and offers conclusions on the form of final limiting distributions (e.g., simulated outputs for product functions approach log normal) if specific mathematical conditions are met. The precise degree to which the conditions must be fulfilled for the technique to yield a useful result in the present application have not yet been fully explored.

While the examples considered here are experimental determination of (1) water solubility, (2) octanol-water partition coefficient, (3) vapor pressure, and (4) volatilization from water, the resulting distributions presumably then could become inputs to larger problems such as determining media-specific environmental concentration, in turn expressed as a well-characterized distribution.

Simulation of Method Error

The process used for determining a distribution of aqueous solubility values involves assuming a "true" solubility value equal to 1.00 arbitrary units, assigning an error distribution for each recognized error source, and calculating the effect on true value of the several sources of error. After assigning

the "true" value, random numbers generated by computer program were used to pick input values within the solubility range of concern. The corresponding error was then calculated for the source first affecting the solubility determination. The resulting discrete error was added to or subtracted from the true value and the resultant used as input to the distribution for the second-occurring error source. Contributions from sources operating simultaneously, rather than sequentially, were calculated and summed simultaneously. This process is repeated to include all recognized sources and results in a single solubility value corresponding to the single random number originally chosen.

The process of choosing a random number and calculation of cascading error is repeated 10,000 times, generating a distribution of solubility values relative to the "true" value which can be characterized mathematically, plotted, and used to furnish the likelihood or probability of any particular solubility value in the range being exceeded. Essentially the same steps were followed in simulations for other parameters investigated, even for those on vapor pressure, where effects of temperature variation are compound-specific.

The calculation procedures used are available in software of the Statistical Analysis System (SAS), version 82-3. Central processing unit time per output distribution on a main frame computer (IBM Model 3280) was around 20 seconds and cost per output distribution was less than $6.

Distributions generated by the process described above may not be easy to label as "normal" or "skewed log-normal", for example, but in general (for Pearson distributions) they are completely characterized by specifying the first four statistical moments, i.e. mean, variance, skew, and kurtosis (3). Consequently, rather than supplying less quantitative labels, these moments are provided for all output distributions which follow. Comparisons with experimental results in the text are limited to discussion of the mean and the square root of variance or standard deviation, because few experiments (and none located in this study) are repeated often enough to generate data sets allowing meaningful calculation of third and fourth moments.

"Beta functions" have been used to represent several sources of error. The beta function is extremely flexible in the sense that it can assume a great variety of shapes depending on values chosen for exponents, as seen in Figure 1, and seems particularly useful in representing negative bias.

Experimental Methods for Solubility Determination

Solubility data for organic compounds in water are obtained readily for highly soluble materials, but for sparingly soluble compounds measurements can be difficult due to potential losses to air or to the container walls, long equilibration times, need for extreme purity in starting materials, and possibly unanticipated minor reactions in solution. As a result, errors of an order of magnitude for some compounds have been reported by MacKay et al. (4).

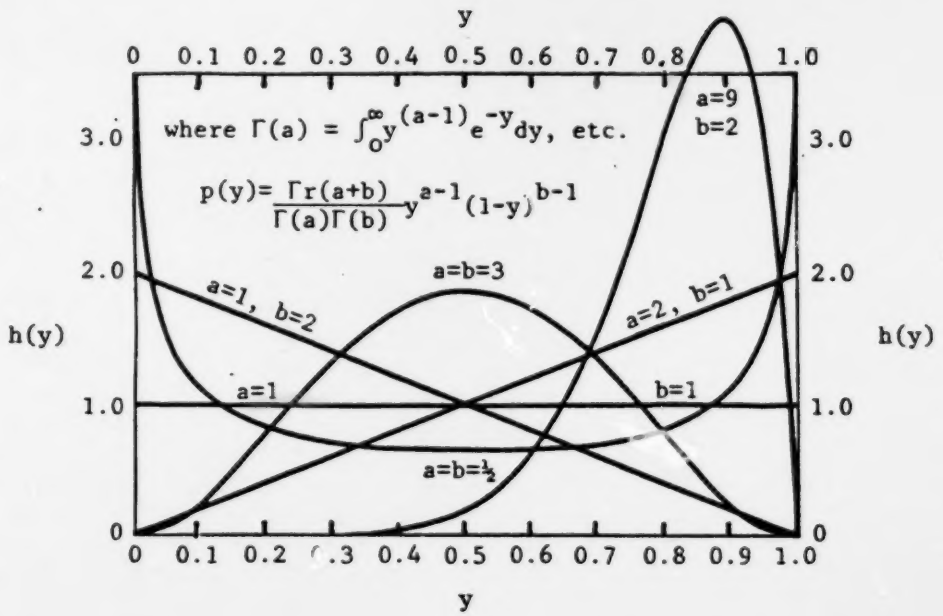


Figure 1. Beta density functions. Reproduced with permission from Ref. 20. Copyright 1970, Houghton Mifflin Co., Boston.

For slightly soluble compounds, two methods dominate the current literature, the shake-flask method, and the generator column method. In the shake-flask (or stir-flask) method, a known amount of solute exceeding the anticipated solubility limit is added to a measured water sample in a sealed container. This mixture is shaken or stirred thoroughly and then allowed to sit for eight hours to several days to ensure that solute-solvent equilibrium is attained. The mixture is then filtered or centrifuged to remove suspended particles, and the solution concentration is determined using customary chromatographic or spectrascopic techniques. Changing range within a method may affect error.

The column generator (and related HPLC) method of determining aqueous solubility has become the predominant method in the literature over the past 5 years. In this method, a column is packed with an inert solid support which provides a high surface area for the solute to insure quick equilibration between it and the aqueous phase. After the support is impregnated with the solute of interest and excess solute has been displaced, the column is brought to the desired temperature and the aqueous concentration is determined as a function of flow rate. The equilibrium concentration corresponds to the highest eluting flow rate where solute concentration remains flow-independent.

Sources of Error in Solubility Determination

The shake-flask method for determining solubility has four major sources of determinate error associated with it. In the first category are losses from adsorption of the solute on the flask walls or to evaporation. This quantity is somewhat dependent on the vapor pressure of the solute in question, but if the quantity of solution used is fairly large (i.e., 250 ml), these losses may represent a maximum of 5 percent of the total solute. A beta distribution was chosen for this error source. The presence of undissolved solute suspended in the water phase may cause a sample to register anomalously high solubility. Centrifuging or filtering reduces this contribution, although the problem may persist for more neutrally bouyant solutes. This error is represented by an exponential distribution with the very low standard deviation expected if the technique described by Karickhoff and Brown (5) is properly followed (±2 percent with 95-percent confidence).

The third source arises from the extraction efficiency for the removal of solute from water, a technique common to most methods. Peters (6), has shown this to introduce another negative bias within 8 percent; therefore a beta distribution with a 95-percent confidence level of -8 percent was selected. Finally, the accuracy of the detection method was modeled by a normal distribution with a 95-percent confidence level of ±2 percent as recommended by Mallon and Harrison (7).

Note that the error introduced by each step is based upon the exit concentration of solute from the previous step and, therefore, is multiplicative in nature. In line with the conclusions of Whitmore (2), the resulting output distribution

might then be expected to approximate log-normality. However, the results of the computer simulation of error for aqueous solubility by the shake-flask method shown in Figure 2 clearly exhibit a negative bias. This bias was introduced by potential losses and by extraction efficiency, although the standard deviation of 3.9 percent compares quite favorably to that cited by several researchers. The mean simulated value underestimates the true value by slightly over 2 percent.

The column method also has several steps which may result in a negative bias on measured aqueous solubility. The lack of water-solute equilibrium in the generator column itself may produce an outlet concentration lower than the "true" solubility according to Stolzenburg and Andren (8). This result also has been modeled with a beta distribution (95-percent confidence level of -3 percent).

The efficiencies for adsorption and extraction steps again are estimated to be similar to those suggested by Peters (6), therefore, the same beta distributions as before are employed. However, note that for the column generator, two-step organic removal typically is used. Finally, one may ascribe the same detection limits as those obtained for the shake-flask method.

The column method results (Figure 3) exhibit a mean simulated value 7 percent under the true value, or 5 percent less than that obtained simulating the shake-flask method. The difference may be attributed to the additional extraction step and solute-equilibration step in the column method. The tendency of this method to underpredict reaffirms the need for calibration of the column system via shake-flask standards prior to use, although the predicted standard deviation of 4 percent is quite good.

Methods and Error in Octanol-Water Partition Coefficient Determinations

The octanol-water-partition coefficient (K_{ow}) is the most frequently cited measure of environmental partitioning behavior. Partition coefficients traditionally have been determined by some variation on the shake-flask method, however, over the past several years high-pressure liquid chromatography has been shown to measure octanol-water partition coefficients accurately over a wide range of values with greater ease.

Since the column/HPLC and shake-flask methods are also the main source of solubility values, the evaluation of error for K_{ow} is very similar. Loss of solute to walls or the atmosphere are still of concern, as are the extraction efficiencies for solute removal from water. Equilibration of each of the three phases involved (instead of two for solubility) is of concern.

The shake-flask method for K_{ow} differs from the solubility determination only in the measurement of solute concentration in the octanol phase. Since this typically involves standard chromatographic or spectroscopic techniques, error again was assumed to be normally distributed about the true concentration with a 95-percent confidence level of ± 2 percent.

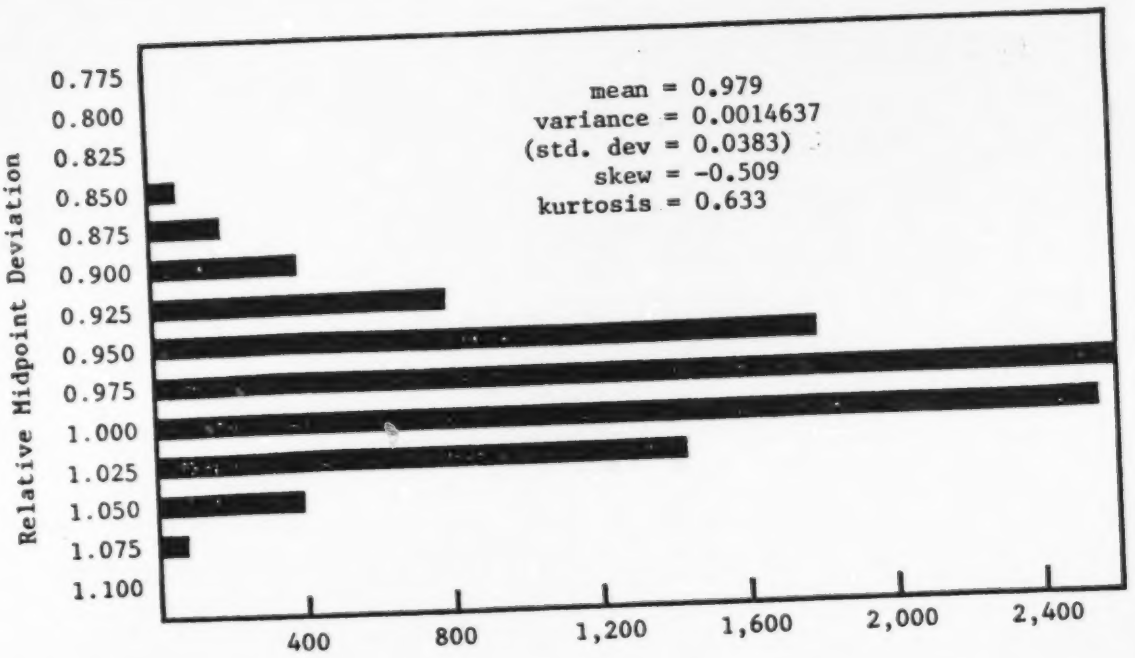


Figure 2. Distribution of simulated aqueous solubility from the shake-flask method (true value = 1.00).

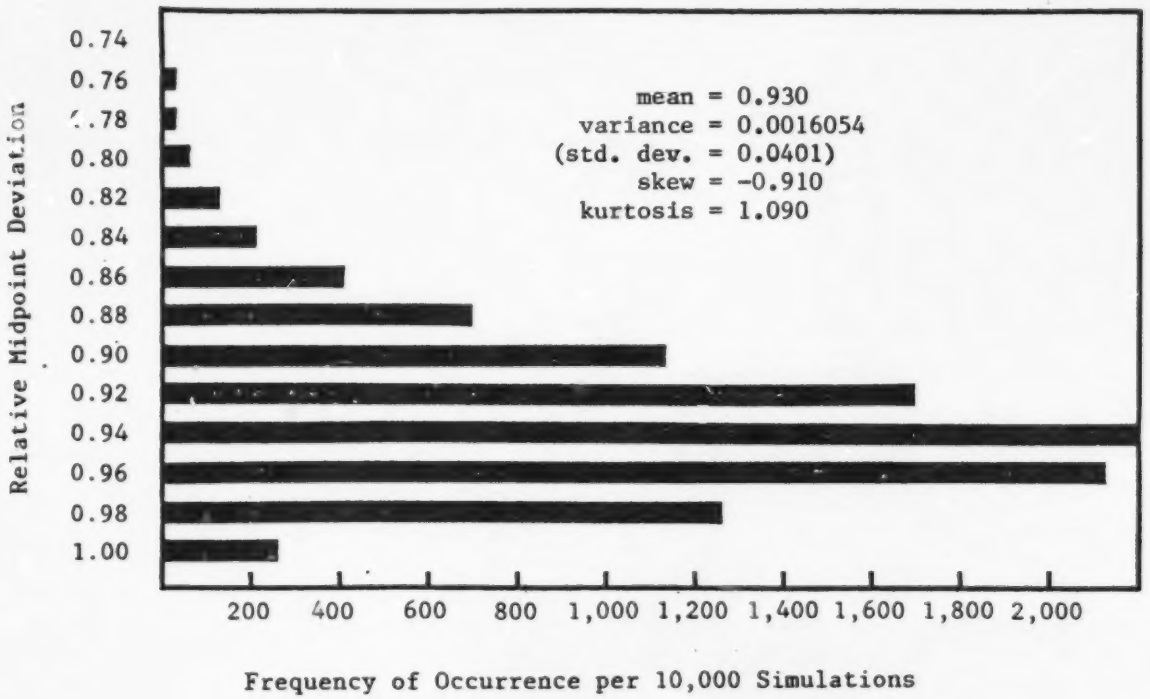


Figure 3. Distribution of simulated aqueous solubility from the column method (true value = 1.00).

Examination of Figure 4 illustrates the tendency of this technique to slightly overpredict K_{ow}. The mean value observed exceeds the true value by 2.3 percent. The standard deviation of 10 percent is somewhat in excess of the 6.1 percent given by Unger et al. (9) and the 8 percent given by Bowman and Sans (10).

The column method for determining K_{ow} involves the equilibration of a solute from a stationary phase (in this case a simulated octanol phase) into an aqueous phase (or methanol-water phase). The solute is then extracted from water and analyzed using an appropriate detector.

Comparison of the column method K_{ow} results with the results given by the column method for solubility in Figure 3 shows the shape of the distributions to be virtually identical with standard deviations being 4.0 percent for solubility and 4.2 percent for K_{ow}. This corresponds to the similarities noted by DeVoe et al., (11). The column method, however, differs from the shake-flask by 9.2 percent in the case of K_{ow} (versus 5 percent for solubility). Woodburn et al. (12) quote a difference of 10 percent between techniques. As indicated by comparing standard deviations, the column method seems as reproducible as the shake-flask method, but accurate calibration is even more necessary to prevent underprediction than was the case for column method for solubility.

Methods for Vapor Pressure Determination

Methods used to determine the vapor pressure of pure compounds are usually divided into two groups based on pressure ranges to which they apply: (1) between 1.0 and 760 torr, and (2) below 1.0 torr.

Manometric Methods. Direct manometry methods such as the isoteniscope method are most often used for the pressure range of 1.0 to 760 torr. The method for the isoteniscope is described in detail in ASTM Method D-2879-70 (13). Figure 5 shows a schematic of the isoteniscope. The sample bulb and short leg of the manometer are filled with the liquid of interest and isoteniscope is attached to a vacuum source. Dissolved gases are removed from the liquid by reducing the system pressure to approximately 1 torr and carefully warming the liquid to its boiling point. The resulting vapor is used to force a small amount of the liquid into the manometer section which traps some vapor between the manometer and bulb. The entire device is placed in a constant temperature bath until equilibrium between liquid and vapor is achieved. Nitrogen is added to the side of the manometer opposite to the sample bulb, until both liquid legs in the manometer section are equal. At that point, the nitrogen pressure is determined and recorded. A McLeod gauge usually is used between 15 and 760 torr. This procedure typically is replicated for temperature increments of 25°C until a system pressure of 760 torr is obtained.

The data obtained in this manner are plotted in terms of the Antoine equation, which relates the natural logarithm of pressure to the reciprocal of absolute temperature:

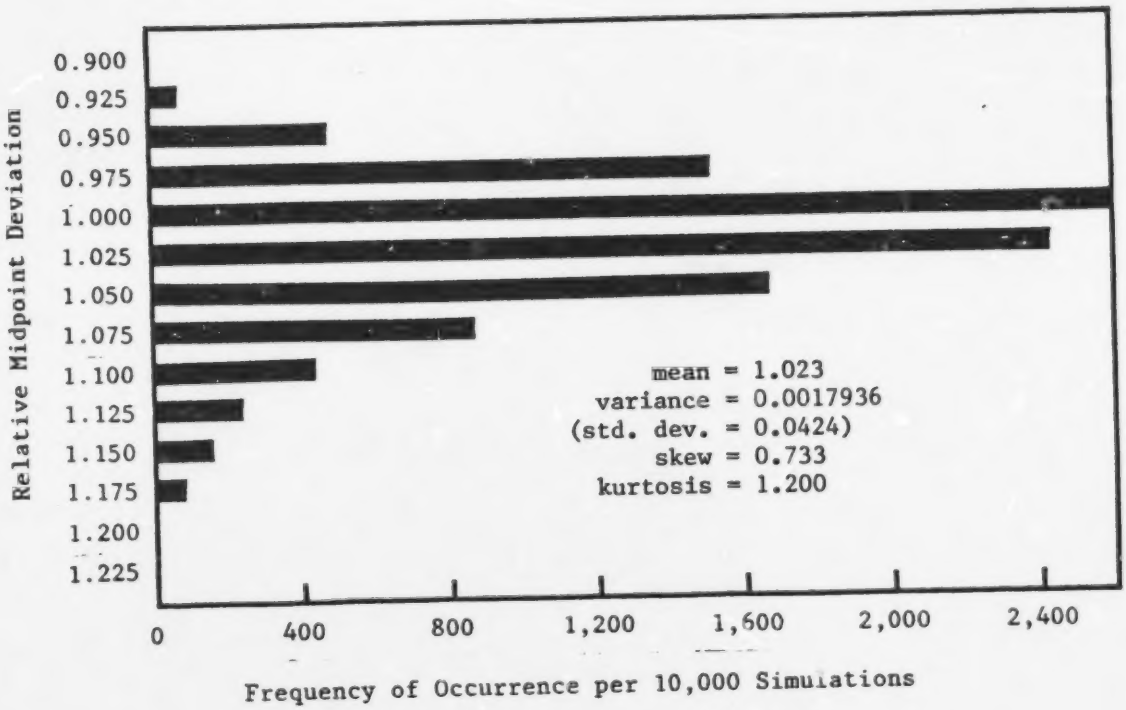


Figure 4. Distribution of simulated octanol-water partition coefficient from the shake-flask method (true value = 1.00).

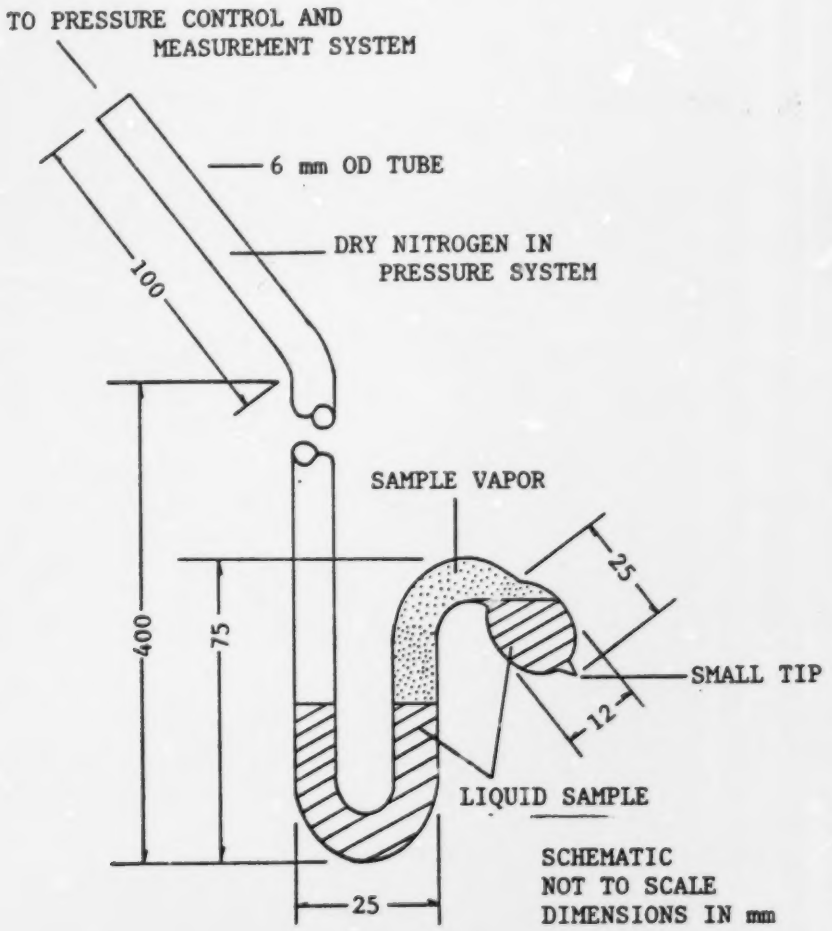


Figure 5. Schematic of an Isoteniscope. Reproduced with permission from Ref. 13. Copyright 1974, American Society for Testing and Materials, Washington, D.C.

$$\ln P_{vapor} = A + \frac{B}{(T + C)}, \qquad (1)$$

where A, B, and C are constants for a given compound. (For this study, rounded "true values" were assumed for vapor pressure, as noted in the text and figures which follow, rather than inserting specific values of A, B, and C for each compound.)

The isoteniscope measurement contains three major sources of error. Two of these sources are independent of pressure. The mercury manometer accuracy of ±1 torr is set as a standard normal distribution about the "true" pressure. The question of sample purity is addressed in the ASTM methodology, with a maximum upward bias of 1 torr on the vapor pressure assured by using this technique. A log-normal distribution with a mean to 0.1 torr is chosen as the representative model based upon suggestions by Osborn and Scott (14). Since these errors are simultaneous in nature and independent of sample pressure, they are taken to be additive.

To determine the overall effect on pressure error of normally distributed variation in temperature, the Antoine equation must be employed. Thus, the pressure error is a function of the compound of interest. To focus on typical situations, three compounds representative of the range of application of the isoteniscope were used. These were: benzene with a relatively high vapor pressure ("true value" = 95 torr at 25°C); toluene for a medium vapor pressure ("true value" = 28 torr at 25°C); and chlorobenzene for a low vapor pressure ("true value" = 12 torr at 25°C).

The results of isoteniscope simulations show a slight overprediction for all three compounds with a skewed distribution in each case (Figures 6, 7, and 8). Predictably, the lower the vapor pressure, the larger the relative standard deviation. On the other hand, the absolute standard deviation is relatively unchanged over the range of vapor pressures examined, varying between about 0.72 and 0.77 torr for the extreme cases. The maximum skewedness of the distribution is found for toluene, the medium-vapor pressure case. The standard deviation of 2.7 percent found for toluene corresponds quite well to the 3 percent error estimate made by MacKay et al. (4). The 6 percent standard deviation for the chlorobenzene case shows it to be at the lower end of the range recommended for reliable measurement. Figure 9 summarizes the isoteniscope simulations, indicating a small tendency of the method to overpredict in the overall pressure range for the three compounds considered.

Gas Saturation Method. For vapor pressures less than 1 torr, a gas saturation method is most often employed. The effusion method or Knudsen method also has been used in this pressure range, but it has proved quite imprecise (15).

The gas saturation method relies upon measurement of vapor loss rates from surfaces for a known volume of gas passed over the surface. While there are several variations on the technique, including ones using HPLC, the one described by Spencer et al. (15) is typical. Dry nitrogen is passed through a quartz sand

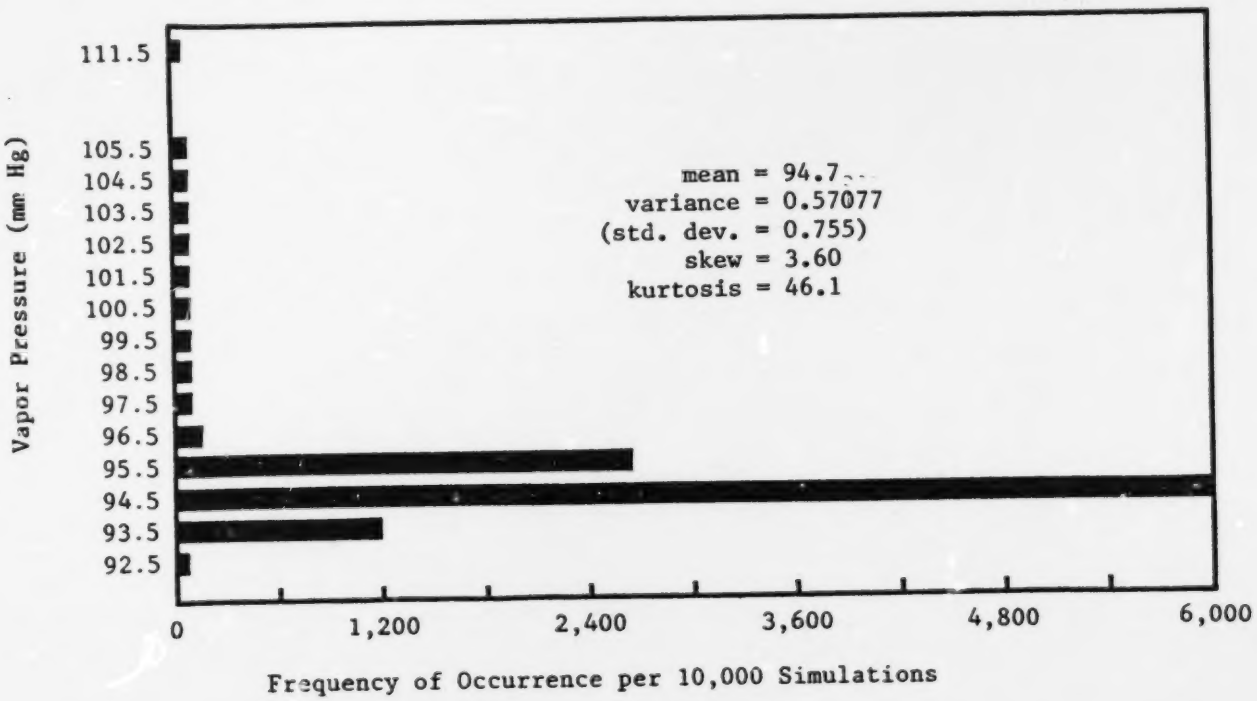


Figure 6. Distribution of simulated vapor pressure for benzene using the isoteniscope.("true value" = 95.0 mm Hg).

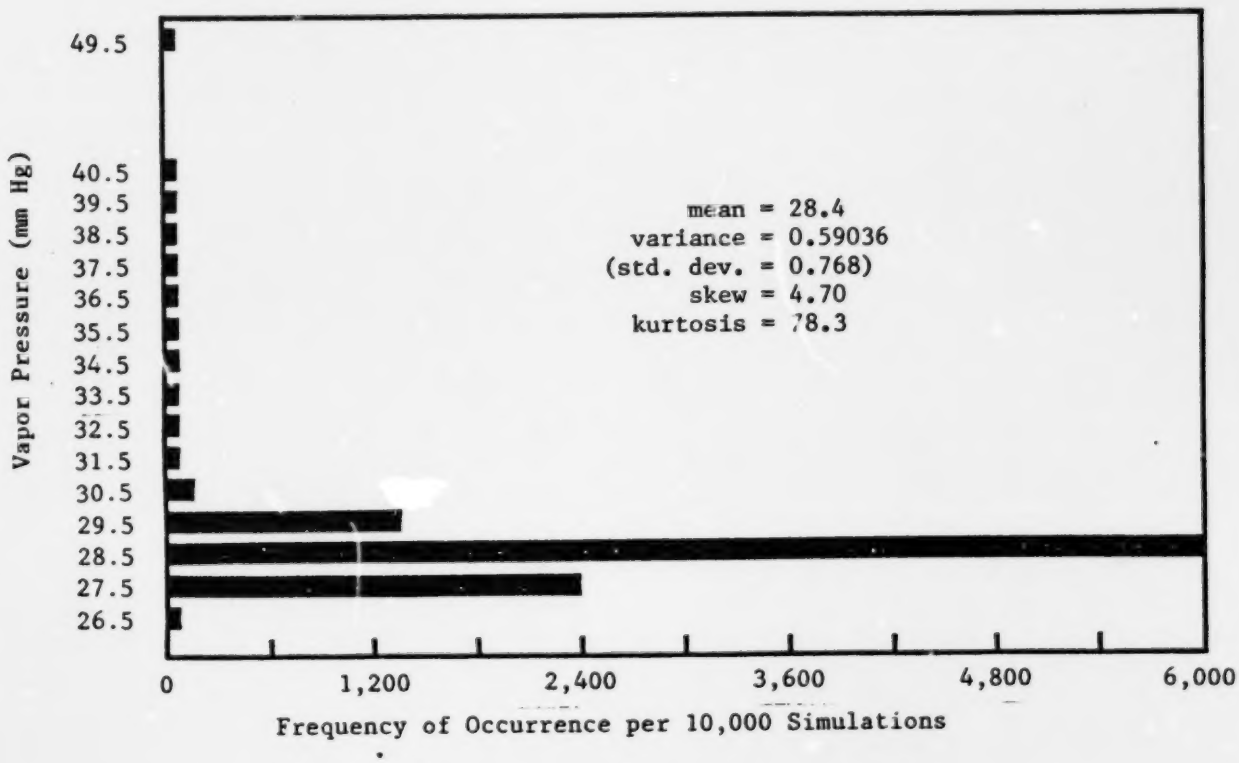


Figure 7. Distribution of simulated vapor pressure for toluene using the isoteniscope ("true value" = 28.0 mm Hg).

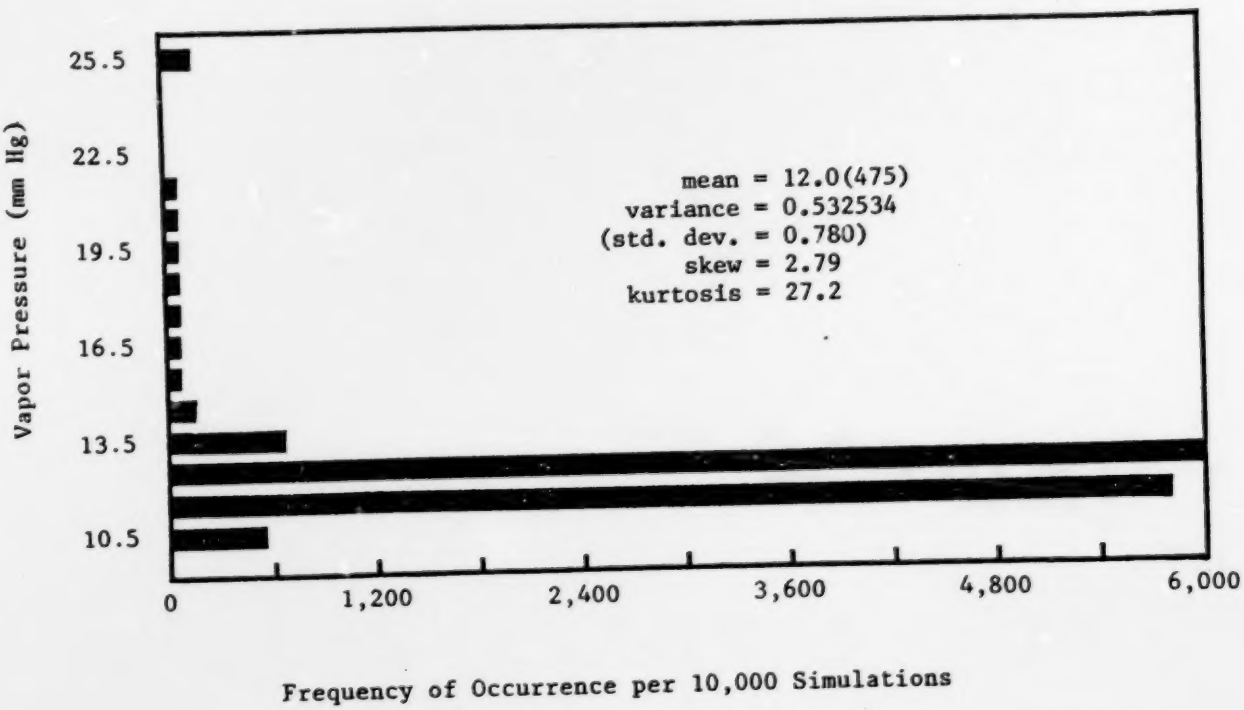


Figure 8. Distribution of simulated vapor pressure for chlorobenzene using the isoteniscope ("true value" = 12.0 mm Hg).

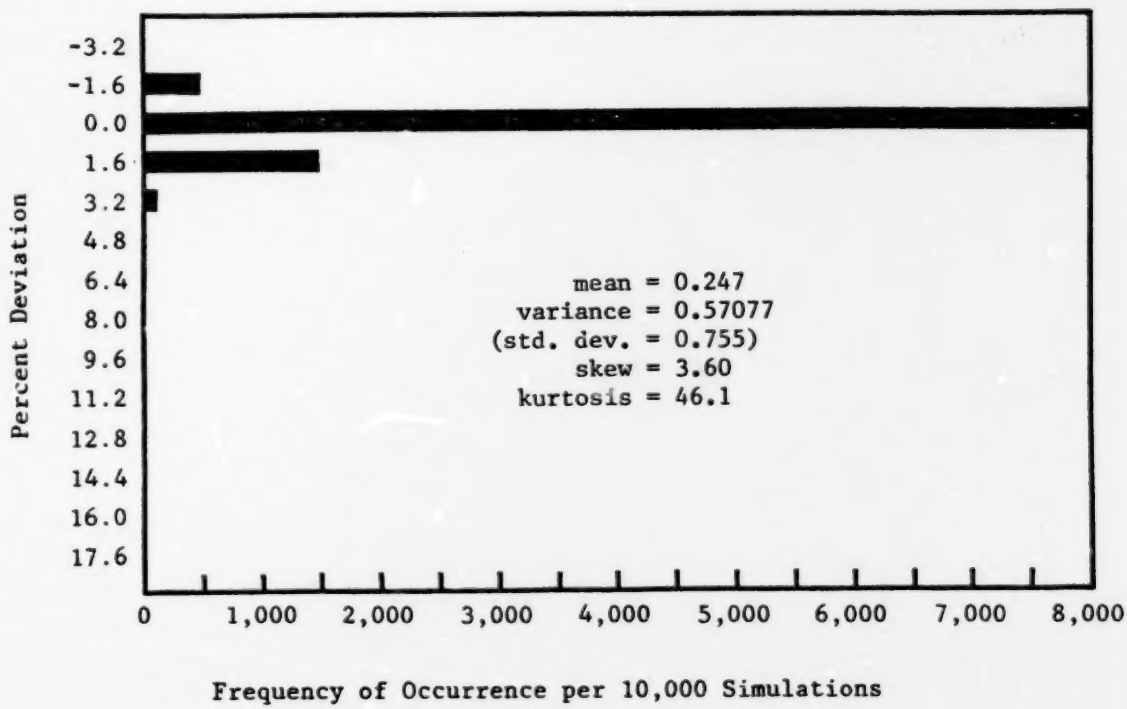


Figure 9. Distribution of relative error for the three vapor pressure simulations (true value = 0.00).

(or other support material) that has been saturated previously with the compound of interest. The vapor that is evolved from this column is trapped on a appropriate sorbent material, which is subsequently extracted and concentrated with a hexane/acetone solution. The concentration of the sample compound in the extract may then be determined using gas chromatography or other detection methods. The vapor phase concentration at equilibrium conditions may be calculated based upon the volume of carrier gas that is used to collect a measured amount of solute in the extract. This procedure is repeated for 10°C temperature increments, and the data are plotted as ln P_{vapor} versus reciprocal absolute temperature (Antoine equation).

The gas saturation method obviously suffers from errors of a different nature than the isoteniscope method. Vapor lost to surfaces within the measurement system and low vapor-trapping efficiency may lead to significant errors for low vapor pressure compounds. Spencer et al. (15) found vapor capture efficiencies as low as 90 percent, while Wasik, et al. (16) arrived at a 95-percent confidence level of ±9 percent. Thomas and Sieber (17) reportedly obtained an error of ±1 to 3 percent using a column-gas saturator. Spencer noted, however, that for some very low vapor pressure compounds, up to an order of magnitude variation has been reported.

For the gas saturation method, the error sources and their approximate values are very similar to previous column techniques. [At 95% confidence, temperature control = ±0.05°K (normal), lack of vapor-liquid equilibrium = -5% (beta), trapping efficiency = -8% (beta), extraction efficiency = -8% (beta), gas chromatographic measurement = ±2% (normal).] Consequently, the error distribution for all three column methods should be approximately the same. This means a general underprediction of vapor pressure as shown in Figure 3.

Effusion Method. The effusion or Knudsen cell method is much less reliable than the gas saturation method. The measurement is based upon weighing a pure sample before and after diffusion of vapor from the sample through an apperture of known cross section into a high vacuum system. Weight loss per unit time then is used to calculate vapor pressure. Unfortunately, the weight loss is the small difference between two relatively large numbers and also proves to be highly dependent on effusion times used, temperature control, and sample purity. Although effusion method data have been reported for materials with vapor pressures as low as 5×10^{-6} torr, DePablo (18) reported up to ±0.3 torr error at measurements of 1 torr (or 30-percent error with 95-percent confidence). Consequently, detailed statistical analysis was not considered worthwhile.

Volatilization from Water

Volatilization from water, the transport of a chemical in solution in a water body to the atmosphere, is believed to be the principal

aquatic fate of low molecular weight, nonpolar compounds that are not otherwise rapidly degraded or transformed (19). The estimation of compound volatilization from a natural water body can be made on the basis of laboratory-measured rate constants, with extrapolation to estimate the activity in the natural environment typically performed in subsequent calculations. For compounds of differing levels of volatility, the rate constants that are required for extrapolation differ. Selection of the appropriate rate constant may be made using results of screening tests.

Test protocols are available for high, medium, and low volatility compounds. However, only the high volatility compound protocol has undergone more than preliminary validation studies. The categorization of compounds into high, medium, and low volatility classes is accomplished by performance of a screening test protocol on the selected compound. The principal reference for the test protocol description and background information is a report prepared by SRI International under contract to the U.S. Environmental Protection Agency by Mill, et al. (19).

The recommended error estimation methods for high volatility compounds from the reference are reviewed in this section of the report after describing the test protocol procedures. A Monte Carlo simulation of experimental results was then performed followed by statistical analyses to determine the distribution and amount of error associated with estimation of volatilization from water for a high volatility compound.

Description of Procedures -- Screening Test. Because the experimental protocols are of recent origin and the reference is not readily available to many readers, they are described here in some detail. The initial step in the SRI procedure is to classify the compound as low, medium, or high volatility and to identfy those compounds with a volatilization half-life of less than 3 months. The following physical property data are necessary to perform the screening test: (1) melting point, (2) Henry's Law constant, or (3) water solubility and vapor pressure at 20°C, and (4) heat of fusion, if the chemical is solid at 20°C and the vapor pressure data used to calculate the Henry's Law constant are for a liquid. The compounds are classified by calculating the Henry's law constant, H_c. The following classification scheme applies:

High volatility: $H_c > 1{,}000$ torr/mole/liter
Intermediate volatility: $10 < H_c < 1{,}000$ torr/mole/liter
Low volatility: $H_c < 10$ torr/mole/liter

The detailed test protocols are recommended for those compounds falling in the class of high or intermediate volatility. For low volatility compounds, the detailed test protocol is recommended if the screening study suggests that other processes, such as photolysis and biodegradation, are slow.

High Volatility Compounds Protocol. The estimated rate constant

of volatilization in the natural environment, $(K_v^c)_{env}$, is based on the laboratory-measured ratio of volatilization rate constant to the oxygen reaeration rate constant $(K_v^c/K_v^o)_{lab}$ by the equation:

$$(K_v^c)_{env} = (K_v^c/K_v^o)_{lab} (K_v^o)_{env} \quad (2)$$

The environmental oxygen reaeration rate constants $(K_v^o)_{env}$ are available for representative bodies of water in Mill, et al. (19). The detailed test protocol provides the procedures for estimating $(K_v^c/K_v^o)_{lab}$.

Measurements are performed in a 2-liter beaker with two tubing connections at the bottom, a constant-speed stirring motor with propeller to stir the solutions, and a recirculating pump that draws solution out of the beaker past a dissolved oxygen analyzer membrane and returns it to the beaker. The initial measurments determine the relationship between K_v^o and stirring rate in the beaker without any of the compound present in the distilled water. After establishing the stirring rate to K_v^o relationship, stock solution on the test compound is added to the distilled water, and the determination of $(K_v^c/K_v^o)_{lab}$ is begun.

Each experimental run is performed at a constant stirring speed. Oxygen content in the solution is monitored and the content recorded periodically. Aliquots of the solution are withdrawn from the beaker periodically, and the concentration of compound in the aliquot is measured. For each experimental run at a stirring speed, at least 10 measurements of concentration of compound must be made, and at least 15 observations of oxygen concentration must be made before the run is completed. Additional experimental runs are required so that data are obtained at no less than six stirring rates, producing a wide range of K_v^o values.

The volatilization rate of the chemical compound is given by the equation,

$$R_v^c = \frac{d[C]}{dt} = -K_v^c [C]_t , \quad (3)$$

where K_v^c is the volatilization rate constant and $[C]_t$ is the concentration of the chemical compound in solution at time t. The oxygen reaeration rate of the solution is given by the equation,

$$R_v^o = \frac{d[O_2]}{dt} = -K_v^o ([O_2]_s - [O_2]_t), \quad (4)$$

where K_v^o is the oxygen reaeration rate constant, $[O_2]_s$ is the dissolved oxygen concentration of the solution at saturation, and $[O_2]_t$ is the dissolved oxygen concentration in solution at time t.

Error Analysis -- High Volatility Compounds. The test protocol requires measurements of both dissolved oxygen and chemical compound as a function of time. Equations 2 and 3, when integrated, show the linear relationship between ln[C] and time t for the chemical compound, and ln $([O_2]_s - [O_2])$ and time t for dissolved oxygen content. The respective slopes for each line are K_v^c and K_v^o, the rate constants. Potential sources of error in this protocol are the individual dissolved oxygen and chemical compound concentration measurements.

The estimated volatilization rate constant K_v^c, is related to the measured concentration and time by the following regression equation:

$$K_v^c = \left[\frac{n\Sigma t \ln C - \Sigma t \, \Sigma \ln C}{n\Sigma t^2 - (\Sigma t)^2} \right], \qquad (5)$$

where n is the number of concentration measurements. At time t = 0, the intercept C_o can be calculated from the following equation:

$$\ln C_o = 1/n \, (\Sigma \ln C - K_v^c \, \Sigma t) \qquad (6)$$

No information presented in the reference document suggests typical values for errors associated with the concentration measurements, or the type of statistical distribution that might represent these errors. The document does suggest that the preferred measurement of error is a 95-percent confidence limit based on the t-statistic, implying that the error distribution is normal in appearance. The equation presented to compute the 95-percent confidence limit was incorrect in the reference. The following equation is the correct form:

$$CL\ (95\%) = t_{n-2,0.05} \left[\frac{\Sigma(\ln C)^2 - \ln C_o \Sigma \ln C - K_v^c \Sigma(\ln C)(t)}{(n-2)\,[\Sigma t^2 - (\Sigma t)^2/n]} \right]^{1/2} \qquad (7)$$

where $t_{n-2,0.05}$ is the two-tailed t-statistic for n-2 degrees of freedom. The confidence interval on K_v^c is as follows:

$$K_v^c - CL < K_v^c < K_v^c + CL$$

The estimated oxygen reaeration rate constant is related to the dissolved oxygen concentration measurements and time by the following regression equations:

$$K_v^o = \left[\frac{n\Sigma(t)\,[\ln (C_s - C)] - \Sigma t\, \Sigma \ln (C_s - C)}{n\Sigma t^2 - (\Sigma t)^2} \right] \qquad (8)$$

where C_s and C are substituted for $[O_2]_s$ and $[O_2]_t$ in Equation 3. Similarity between Equations 4 and 7 is readily apparent. The equation for the intercept C_o is:

$$\ln(C_s - C_o) = 1/n\,[\Sigma \ln (C_s - C) - K_v^o\, \Sigma t], \qquad (9)$$

also similar to Equation 5. As in the case of K_v^c, there is no information in the reference text regarding typical error values for measurements of dissolved oxygen concentration or the type of statistical distribution representative of those errors. An equation is presented to calculate a 95-percent confidence limit using the t-statistic, thus making the assumption of near normally distributed errors apparent. The text listed an incorrect form of the equation; the correct form is as follows:

$$CL(95\%) = t_{n-2,0.05}$$

$$X \left[\frac{\Sigma[\ln(C_s-C)]^2 - \ln(C_s-C_o)\Sigma\ln(C_s-C) - K_v^o\Sigma(t)[\ln(C_s-C)}{(n-2)\,[\Sigma t^2 - (\Sigma t)^2/n]} \right]^{1/2} \qquad (10)$$

As in the case of Equation 6, t is the two-tailed t-statistic with n-2 degrees of freedom.

Given at lease six values of K_v^c and K_v^o obtained over a range of stirring rates, the ratio of (K_v^c/K_v^o) can be obtained by plotting the data points and fitting a linear least squares line through the data points forced through the origin. The equation for this regression line is given as:

$$(K_v^c/K_v^o) = \left[\frac{\Sigma(K_v^o)_j (K_v^c)_j}{\Sigma(K_v^o)_j^2} \right] \qquad (11)$$

where the subscript j refers to the j^{th} measurement (stirring rate) of K_v^c and K_v^o. The quotient (K_v^c/K_v^o) is also assumed to be t-distributed in the reference. The equation for the 95-percent confidence level is given as:

$$CL\ (95\%) = t_{n-1,\ 0.05} \left[\frac{\Sigma (K_v^c)_j^2 - (K_v^o/K_v^o)\Sigma (K_v^o)_j\ (K_v^c)_j}{(n-1)\ \Sigma (K_v^o)_j^2} \right]^{1/2} \qquad (12)$$

The reference indicates that the 95-percent confidence limit on the average of (K_v^c/K_v^o) for high volatility compounds is about 5 to 10 percent of the magnitude of (K_v^c/K_v^o).

Simulation of Experimental Results and Error Estimation. An analysis of implied normality of error associated with measurements of K_v^c and K_v^o is not possible because of the lack of experimental data. However, even if the normality of error in measuring K_v^c and K_v^o is assumed, it is not ncessarily true that the estimated ratio of the two rate constants, (K_v^c/K_v^o), will have normally distributed errors as is assumed in the reference text. Further, the use of the linear regression approach to determine (K_v^c/K_v^o) may tend to underestimate (K_v^c/K_v^o) because the errors in determining K_v^o are taken into account. Likewise, the variance of (K_v^c/K_v^o) may be underestimated for the same reason.

To examine the reasonableness of the assumed near normality for (K_v^c/K_v^o) and the potential for the underestimation of the slope and its variance, Monte Carlo simulations were performed. For the simulations, a true mean value of (K_v^c/K_v^o) was selected as 0.71. The selection was based on an actually measured value of (K_v^c/K_v^o) for 1,1-dichloroethane over a range of K_v values of 0.3 to 12.0 hr^{-1} (19). Using this ratio and six assumed values of K_v^o corresponding to varied stirring rates) within the recommended experimental range of 1 to 15 hr^{-1}, a set of six corresponding K_v^c were calculated. These mean values are shown in Table I.

For the first simulation, it was assumed that the relative accuracy of determining K_v^o and K_v^c was such that 95 percent of the measured values would fall within the range of ± 5 percent of their true mean values, listed in Table I. It was also assumed that the measured value errors were t-distributed, thus allowing computation of standard deviations also shown in Table I. For the second simulation, it was assumed that 95 percent of the measured K_v^o and K_v^c would fall within the range of ± 10 percent using the same mean K_v^o and K_v^c as assumed for the first simulation. The resultant standard deviations are also shown in Table I.

After completing the computation of the mean K_v^o and K_v^c and standard deviations, a random number generator was used to develop 1,000 normally distributed values of each K_v^o and K_v^c, having the listed standard deviations. Verification of the normality of the randomly generated number sets was done by a Chi-square test on each number set.

The next steps were to compute the ratio of (K_v^c/K_v^o)

Table I. Simulation Mean and Standard Deviations[a]

Run No.		Mean Value	Simulation 1 Standard Deviation	Simulation 2 Standard Deviation
K_v^o	1	2.5	0.0486	0.0972
	2	4.0	0.0778	0.1556
	3	6.0	0.1167	0.2334
	4	8.3	0.1615	0.3229
	5	10.6	0.2062	0.4123
	6	13.1	0.2548	0.5095
K_v^c	1	1.78	0.0345	0.0690
	2	2.84	0.0552	0.1105
	3	4.26	0.0828	0.1657
	4	5.89	0.1146	0.2292
	5	7.53	0.1464	0.2927
	6	9.30	0.1809	0.3618

[a]A total of 1,000 values were used in each simulation.

corresponding to each of the six values of K_v^o (six stirring speeds) and to compute (K_v^c/K_v^o) from Equation 11 for each of the 1,000 trials. The standard deviation corresponding to each of the 1,000 estimated (K_v^c/K_v^o) were computed using the bracketed portion of Equation 12. The results of these computations are summarized in Table II for both simulations.

Table II. Simulation Test Results

Parameter	Simulation 1	Simulation 2
K_v^c/K_v^o mean	0.7098	0.7107
Low value	0.6779	0.6380
High value	0.7472	0.7766
Standard deviation of mean value	0.0104	0.0208
Average standard deviation of individual slopes	0.00693	0.01359
Other properties of distribution		
Coefficient of skewness	0.9551	0.03318
Kurtosis	-94.8748	4.6605
Chi-square sum	11.44	2.02

The estimated average values of (K_v^c/K_v^o) were in good agreement with the true value, 0.71 (0.7098 and 0.7107 for the ±5 percent and ±10 percent simulations, respectively). Chi-square tests performed on both distributions of (K_v^c/K_v^o) did not reject the hypotheses of normality at the 0.05 level of significance. Therefore, for the two simulations performed, the assumption of normality for the error distribution associated with (K_v^c/K_v^o) seems reasonable.

The question of whether the variance of (K_v^c/K_v^o) is underestimated by using the regression procedure of Equation 11 was studied in the following way. For each of the 1,000 estimated slopes, (K_v^c/K_v^o) the 95-percent confidence interval was calculated using Equation 12. If Equation 12 is a satisfactory estimator for the 95-percent confidence interval, then about 95 percent of the computed confidence intervals should contain the true slope, 0.71. When these calculations were performed on the simulation generated distributions of (K_v^c/K_v^o), only about 86 percent of the supposed 95 percent confidence intervals in each simulation contained the true slope, 0.71. Because the simulation generated estimates of average (K_v^c/K_v^o) were so near the true value of 0.71, it is presumed that the principal reason fewer confidence intervals contained 0.71 than expected is that the variance is underestimated by Equation 12.

As a potential means for correcting for the underestimated variance, the following computations were made. In computing the 95-percent confidence interval, the standard deviation of the individual (K_v^c/K_v^o) in the simulations were multiplied by S_{ga}/S_{iavg} where S_{ga} is the overall standard deviation of 1,000 (K_v^c/K_v^o) in each simulation and S_{iavg} is the average of the standard deviations computed for each of the 1,000 individual (K_v^c/K_v^o). When this correction was applied to computed confidence intervals in both simulations, about 96 percent of the 95-percent confidence intervals contained the true slope of 0.71. When applied to the standard deviation of individual (K_v^c/K_v^o) this correction factor had a value of about 1.5 for both simulations. This suggests that the bracketed portion of Equation 12 may underestimate the variance of (K_v^c/K_v^o) by as much as a factor of 2.3 (i.e., standard deviation by a factor of 1.5).

Conclusions

Column and high performance liquid chromatography (HPLC) methods for measurement of solubility, octanol-water partition coefficient, and vapor pressure which are replacing the older equilibrium methods tend to underestimate aqueous solubility and vapor pressure and tend to overestimate the octanol-water partition coefficient. The standard deviation for both the equilibrium and dynamic systems are similar, but calibration between systems is necessary to insure that they agree. The range of errors for both types of measurement as mentioned in the literature are well within the range predicted by the computer-simulated error

distributions generated in this report. The measurement error distributions that were determined are not normally distributed and show a definite bias for each measured parameter.

The precise number of simulations needed to provide adequate "resolution" for the output distributions was not explored as part of the current study but seems likely to be a simple function of the number of subdividions for the range of output parameter being examined and also should depend, not so simply, on the number and resolution of input distributions, as well as on the probability requirements of the output (i.e., less resolution needed to assure a discrete value, "a", will be exceeded in only 1 out of 10 cases than is needed for only 1 out of 100 cases).

For volatilization from water, the measurement method error associated with determination of the ratio of rate constants, K_v^c/K_v^o, is typically reported in terms of 95-percent confidence limits on the average value. For high volatility compounds, the 95-percent confidence limits are reported to be 5 to 10 percent of the magnitude of (K_v^c/K_v^o). The regression approach typically used to determine (K_v^c/K_v^o) and the specification of confidence limits based on the t-distribution imply that the error distributions are assumed to be normal. However, even if the errors of K_v^c and K_v^o estimates are each normally distributed, the error distribution associated with the quotient of the two is not necessarily normally distributed. The regression approach assumed may produce an estimated value of (K_v^c/K_v^o) lower than the true value and underestimate the variance. Monte Carlo simulation of the regression approach did not confirm underestimation of (K_v^c/K_v^o); however, the variances appeared to be underestimated by a factor of 2.3.

Acknowledgements

The authors wish to express their gratitude to Dr. James W. Falco for the initial suggestion that a stochastic approach might be applicable to uncertainty considerations and also thank Mr. Richard Walentowicz for helpful discussion of Reference 1.

Literature Cited

1. Walentowicz, R.; Falco, J.W. "Stochastic Processes Applied to Risk Analysis of TCDD Contaminated Soil: A Case Study", Unpublished Report, 1984; Exposure Assessment Group, ORD, US EPA, Washington, DC 20460.
2. Whitmore, R.W. "Methodology for Characterization of Uncertainty in Exposure Assessments", 1985; EPA 600/8-85/009, NTIS No. PB85-240445, p. 26.
3. Kendall, M.G.; Stuart, A. "The Advanced Theory of Statistics; Volume 1, Distribution Theory"; Charles Griffin and Co. Ltd.: London, 1958; pp. 152-153.
4. MacKay, D.; Mascarenhas, R; Shiu, W.Y.; Chemosphere, 1980, 9, 257-264.
5. Karickhoff, S.W.; Brown, D.S. "Determination of Octanol-Water-Distribution Coefficients, Water Solubilities, and

Sediment-Water-Partition Coefficients for Hydrophobic Organic Pollutants", 1979; EPA-600/4-79-032, NTIS No. PB 80-103591, U.S. Environmental Protection Agency, Athens, GA.

6. Peters, R.L. Anal. Chem., 1982, 54, 1913-1914.
7. Mallon, B.J.; Harrison, F.L. Bull. Environ. Contam. Toxicol., 1984, 32(3), 316-323.
8. Stolzenburg, T.R.; Andren, A.W. Analytica Chimica Acta 1983, 151, 271-274.
9. Unger, S.H.; Cook, J.R.; Hollenberg, J. J. Pharm. Sci. 1978, 67(10), 1364-1367.
10. Bowman, B.T.; Sans, W.T. Env. Sci. Health, 1983, 18(6), 667-683.
11. DeVoe, H.; M. Miller; Wasik, S. J. Rsch. Natl. Bur. Stds., 1981, 86(4), 361-366.
12. Woodburn, K.B.; Doucette, W.; Andren, A. Environ. Sci. Technol. 1984, 18(6), 457-459.
13. American Society for Testing and Materials (ASTM), ASTM Method D-2879-70. ASTM Standards, Part 24, 1974, Philadelphia, PA.
14. Osborn, A.G.; Scott, D.W. J. Chem. Thermodynamics, 1980, 12, 429-438.
15. Spencer, W.F.; Shoup, T.; Cliath, M. J. Agric. Food Chem. 1979, 27(2), 273-278.
16. Wasik, S.; Tewari, Y; Miller, M. J. Rsch. Natl. Bur. Stds. 1982, 87(4), 311-315.
17. Thomas, T.C.; Sieber, A. Bul. Environ. Contam. Toxicol. 1974, 12, 17-21.
18. DePablo, R.S. J. Phys. D.: Appl. Phys., 13, 313-319.
19. Mill, T.; Mabey, W.R.; Bomberger, D.C. "Laboratory Protocols for Evaluating the Fate of Organic Chemicals in Air and Water." 1982, EPA-600/382-022, NTIS No. PB 3-150888, U.S. Environmental Protection Agency, Athens, GA.
20. Johnson, N.L.; Kotz, S. "Distributions in Statistics: Continuous Univariate Distributions-2"; Houghton Mifflin Co.: Boston, 1970; p. 44.